Table 3-38 MOBILITY Statement Parameters			
Parameter	**Type**	**Default**	**Units**
A.BROOKS	Real	1.56×10^{21}	$(cmV\cdot s)^{-1}$
B.BROOKS	Real	7.63×10^{19}	cm^{-3}
N.BROOKS	Logical	False	
P.BROOKS	Logical	False	

Incomplete Ionization and Doping Dependent Mobility

The default in ATLAS is to use the total doping (N_A+N_D) in the formulae for the doping concentration dependence of low-field mobility (e.g., ARORA model). As an alternative, ATLAS can use the ionized dopant concentration.

The ionized doping concentration is obtained automatically and used in calculating the charge density when you set the INCOMPLETE parameter on the MODELS statement. See Section 3.3.1 "Incomplete Ionization of Impurities" for more information.

ATLAS has a MOB.INCOMPL parameter on the MODELS statement. This allows you to use the ionized dopant concentration to calculate doping dependent mobilities. Specifying this parameter automatically sets the INCOMPLETE parameter. This ensures that the solution is consistent with an ionized rather than total doping concentration.

For high doping levels, the difference between total doping and ionized doping concentrations can be large and so this can result in quite different mobility values.

If it is required to use the ionized dopant concentration for mobility calculations and the total dopant concentration for calculating the charge density in Poisson's equation, then specify MOB.INCOMPL ^INCOMPLETE on the MODELS statement to explicitly clear this flag. This combination of parameters is not recommended.

MOB.INCOMPL affects the ANALYTIC, ARORA, MASETTI, YAMAGUCHI, CVT, KLAASSEN, ALBRECHT and tabulated Low-Field Mobility Models.

Klaassen's Unified Low-Field Mobility Model

The model by D. B. M. Klaassen [138, 139], provides a unified description of majority and minority carrier mobilities. In so doing, it includes the effects of lattice scattering, impurity scattering (with screening from charged carriers), carrier-carrier scattering, and impurity clustering effects at high concentration. The model shows excellent agreement between the modeled and empirical data for:

- majority electron mobility as a function of donor concentration over the range of 10^{14} cm^{-3} to 10^{22} cm^{-3}
- minority electron mobility as a function of acceptor concentration over the range of 10^{17} cm^{3} to 10^{20} cm^{-3}
- minority hole mobility as a function of donor concentration from 10^{17} cm^{-3} to 10^{20} cm^{-3}
- temperature dependence over the range of 70 K to 500 K

The Klaassen Model accounts for a broader set of effects and has been calibrated over a wider range of conditions than any other of the low-field bulk mobility models. This is the recommended model for both MOS and bipolar simulation and is the default model for silicon when you set MOS2 or BIPOLAR2 in the MODELS statement. You can enable or disable the model by using the KLA parameter in the MODELS statement, or independently for electrons and holes by the KLA.N and KLA.P parameters of the MOBILITY statement.

The total mobility can be described by its components using Matthiessen's rule as:

$$\mu_{n0}^{-1} = \mu_{nL}^{-1} + \mu_{nDAP}^{-1} \quad \text{3-200}$$

$$\mu_{p0}^{-1} = \mu_{pL}^{-1} + \mu_{pDAP}^{-1} \quad \text{3-201}$$

μ_n and μ_p are the total low-field electron and hole mobilities, μ_{nL} and μ_{pL} are the electron and hole mobilities due to lattice scattering, μ_{nDAP} and μ_{pDAP} are the electron and hole mobilities due to donor (D), acceptor (A), screening (P) and carrier-carrier scattering.

The lattice scattering components, μ_{nL} and μ_{pL} are given as:

$$\mu_{nL} = \mathtt{MUMAXN.KLA}\left(\frac{300}{T_L}\right)^{\mathtt{THETAN.KLA}} \quad \text{3-202}$$

$$\mu_{pL} = \mathtt{MUMAXP.KLA}\left(\frac{300}{T_L}\right)^{\mathtt{THETAP.KLA}} \quad \text{3-203}$$

where T_L is the temperature in degrees Kelvin. MUMAXN.KLA, MUMAXP.KLA, THETAN.KLA, and THETAP.KLA are user-definable model parameters that can be specified as shown in Table 3-39.

Table 3-39 User-Specifiable Parameters for Equations 3-202 and 3-203

Statement	Parameter	Default	Units
MOBILITY	MUMAXN.KLA	1417.0	$cm^2/(V \cdot s)$
MOBILITY	MUMAXP.KLA	470.5	$cm^2/(V \cdot s)$
MOBILITY	THETAN.KLA	2.285	
MOBILITY	THETAP.KLA	2.247	

The impurity-carrier scattering components of the total mobility are given by:

$$\mu_{nDAP} = \mu_{N,n}\frac{N_{nsc}}{N_{nsc,eff}}\left(\frac{\mathtt{NREF1N.KLA}}{N_{nsc}}\right)^{\mathtt{ALPHA1N.KLA}} + \mu_{nc}\left(\frac{n+p}{N_{nsc,eff}}\right) \quad \text{3-204}$$

$$\mu_{pDAP} = \mu_{N,p}\frac{N_{psc}}{N_{psc,eff}}\left(\frac{\text{NREF1P.KLA}}{N_{psc}}\right)^{\text{ALPHA1P.KLA}} + \mu_{pc}\left(\frac{n+p}{N_{psc,eff}}\right) \quad \text{3-205}$$

Table 3-40 User-Specifiable Parameters for Equations 3-204 and 3-205

Statement	Parameter	Default	Units
MOBILITY	ALPHA1N.KLA	0.68	
MOBILITY	ALPHA1P.KLA	0.719	
MOBILITY	NREF1N.KLA	9.68×10^{16}	cm^3
MOBILITY	NREF1P.KLA	2.23×10^{17}	cm^3

The impurity scattering components, $\mu_{N,n}$ and $\mu_{N,p}$, are given by:

$$\mu_{N,n} = \frac{\text{MUMAXN.KLA}^2}{\text{MUMAXN.KLA} - \text{MUMINN.KLA}}\left(\frac{T_L}{300}\right)^{(3\times\text{ALPHA1N.KLA}-1.5)} \quad \text{3-206}$$

$$\mu_{N,p} = \frac{\text{MUMAXP.KLA}^2}{\text{MUMAXP.KLA} - \text{MUMINP.KLA}}\left(\frac{T_L}{300}\right)^{(3\times\text{ALPHA1P.KLA}-1.5)} \quad \text{3-207}$$

where T_L is the temperature in degrees Kelvin. MUMINN.KLA and MUMINP.KLA are user-defined parameters shown in Table 3-41, and the other parameters are as described in Tables 3-39 and 3-40.

Table 3-41 User-Specifiable Parameters for Equations 3-206 and 3-207

Statement	Parameter	Default	Units
MOBILITY	MUMINN.KLA	52.2	$cm^2/(V\cdot s)$
MOBILITY	MUMINP.KLA	44.9	$cm^2/(V\cdot s)$

The carrier-carrier scattering components, μ_{nc} and μ_{pc}, are given by:

$$\mu_{nc} = \frac{\text{MUMINN.KLA}\times\text{MUMAXN.KLA}}{\text{MUMAXN.KLA}-\text{MUMINN.KLA}}\left(\frac{300}{T_L}\right)^{0.5} \quad \text{3-208}$$

$$\mu_{pc} = \frac{\text{MUMINP.KLA}\times\text{MUMAXP.KLA}}{\text{MUMAXP.KLA}-\text{MUMINP.KLA}}\left(\frac{300}{T_L}\right)^{0.5} \quad \text{3-209}$$

The N_{nsc} and N_{psc} parameters of Equations 3-204 and 3-205 are given by:

$$N_{nsc} = N_D + N_A + p \quad \text{3-210}$$

$$N_{psc} = N_D + N_A + n \quad \text{3-211}$$

where N_D is the donor concentration in cm^{-3}, N_A is the acceptor concentration in cm^{-3}, n is the electron concentration in cm^{-3} and p is the hole concentration in cm^{-3}.

The parameters of Equations 3-204 and 3-205 are given by:

$$N_{nsc,\,eff} = N_D + G(P_n)N_A + \left(\frac{p}{F(P_n)}\right) \quad \text{3-212}$$

$$N_{psc,\,eff} = N_A + G(P_p)N_D + \left(\frac{n}{F(P_p)}\right) \quad \text{3-213}$$

where N_D is the donor concentration in cm^{-3}, N_A is the acceptor concentration in cm^{-3} and n is the electron concentration in cm^{-3} and p is the hole concentration in cm^{-3}. The two functions, $G(P)$ and $F(P)$, are functions of the screening factors, P_n and P_p, for electrons and holes. The function, $G(P)$, in Equations 3-212 and 3-213 are given by:

$$G(P_n) = 1 - \frac{\texttt{S1.KLA}}{\left[\texttt{S2.KLA} + P_n\left(\frac{(T_L/300)}{\texttt{ME.KLA}}\right)^{\texttt{S4.KLA}}\right]^{\texttt{S3.KLA}}} + \frac{\texttt{S5.KLA}}{\left[P_n\left(\frac{\texttt{ME.KLA}}{(T_L/300)}\right)^{\texttt{S7.KLA}}\right]^{\texttt{S6.KLA}}} \quad \text{3-214}$$

$$G(P_p) = 1 - \frac{\texttt{S1.KLA}}{\left[\texttt{S2.KLA} + P_p\left(\frac{(T_L/300)}{\texttt{MH.KLA}}\right)^{\texttt{S4.KLA}}\right]^{\texttt{S3.KLA}}} + \frac{\texttt{S5.KLA}}{\left[P_p\left(\frac{\texttt{MH.KLA}}{(T_L/300)}\right)^{\texttt{S7.KLA}}\right]^{\texttt{S6.KLA}}} \quad \text{3-215}$$

Here, T_L is the temperature in degrees Kelvin, m_e and m_h are the electron and hole masses and the parameters S1.KLA through S7.KLA are user-specifiable model parameters as shown in Table 3-42..

Table 3-42 User-Specifiable Parameters for Equations 3-214 and 3-215

Statement	Parameter	Default	Units
MOBILITY	S1.KLA	0.89233	
MOBILITY	S2.KLA	0.41372	
MOBILITY	S3.KLA	0.19778	
MOBILITY	S4.KLA	0.28227	
MOBILITY	S5.KLA	0.005978	
MOBILITY	S6.KLA	1.80618	
MOBILITY	S7.KLA	0.72169	

The functions, $F(P_n)$ and $F(P_p)$, in Equations 3-212 and 3-213 are given by:

$$F(P_n) = \frac{\mathtt{R1.KLA}\, P_n^{\mathtt{R6.KLA}} + \mathtt{R2.KLA} + \mathtt{R3.KLA}\,\frac{\mathtt{ME.KLA}}{\mathtt{MH.KLA}}}{P_n^{\mathtt{R6.KLA}} + \mathtt{R4.KLA} + \mathtt{R5.KLA}\,\frac{\mathtt{ME.KLA}}{\mathtt{MH.KLA}}} \quad \text{3-216}$$

$$F(P_p) = \frac{\mathtt{R1.KLA}\, P_p^{\mathtt{R6.KLA}} + \mathtt{R2.KLA} + \mathtt{R3.KLA}\,\frac{\mathtt{MH.KLA}}{\mathtt{ME.KLA}}}{P_p^{\mathtt{R6.KLA}} + \mathtt{R4.KLA} + \mathtt{R5.KLA}\,\frac{\mathtt{MH.KLA}}{\mathtt{ME.KLA}}} \quad \text{3-217}$$

where the parameters, R1.KLA through R6.KLA, are user-specifiable as shown in Table 3-43.

Table 3-43 User-Specifiable Parameters for Equations 3-216 and 3-217

Statement	Parameter	Default	Units
MOBILITY	ME.KLA	1.0	
MOBILITY	MH.KLA	1.258	
MOBILITY	R1.KLA	0.7643	
MOBILITY	R2.KLA	2.2999	
MOBILITY	R3.KLA	6.5502	
MOBILITY	R4.KLA	2.3670	
MOBILITY	R5.KLA	-0.8552	
MOBILITY	R6.KLA	0.6478	

The screening parameters, P_n and P_p, used in Equations 3-216 and 3-217 are given by:

$$P_n = \left[\frac{\mathtt{FCW.KLA}}{P_{CW,n}} + \frac{\mathtt{FBH.KLA}}{P_{BH,n}}\right]^{-1} \quad \text{3-218}$$

$$P_p = \left[\frac{\mathtt{FCW.KLA}}{P_{CW,p}} + \frac{\mathtt{FBH.KLA}}{P_{BH,p}}\right]^{-1} \quad \text{3-219}$$

Here, the FCW.KLA and FBH.KLA parameters are user-specifiable model parameters as shown in Table 3-44.

Table 3-44 User-Specifiable Parameters for Equations 3-218 and 3-219			
Statement	**Parameter**	**Default**	**Units**
MOBILITY	FCW.KLA	2.459	
MOBILITY	FBH.KLA	3.828	

The functions, $P_{BH,n}$ and $P_{BH,p}$, $P_{CW,n}$, and $P_{CW,p}$ are given by the following equations.

$$P_{BH,n} = \frac{1.36\times10^{20}}{n}(\mathrm{ME.KLA})\left(\frac{T_L}{300}\right)^2 \quad 3\text{-}220$$

$$P_{BH,p} = \frac{1.36\times10^{20}}{p}(\mathrm{MH.KLA})\left(\frac{T_L}{300}\right)^2 \quad 3\text{-}221$$

$$P_{CW,n} = 3.97\times10^{13}\left\{\frac{1}{Z_n^3 N_D}\left(\frac{T_L}{300}\right)^3\right\}^{\frac{2}{3}} \quad 3\text{-}222$$

$$P_{CW,p} = 3.97\times10^{13}\left\{\frac{1}{Z_p^3 N_A}\left(\frac{T_L}{300}\right)^3\right\}^{\frac{2}{3}} \quad 3\text{-}223$$

where T_L is the temperature in degrees Kelvin, m_e/m_0 and m_h/m_0 are the normalized carrier effective masses, and n and p are the electron and hole concentrations in cm^{-3}.

Also here, N_D and N_A are the donor and acceptor concentrations in cm^{-3}, T_L is the temperature in degrees Kelvin, and Z_n and Z_p are clustering functions given by:

$$Z_n = 1 + \frac{1}{\mathrm{CD.KLA} + \left(\frac{\mathrm{NREFD.KLA}}{N_D}\right)^2} \quad 3\text{-}224$$

$$Z_p = 1 + \frac{1}{\mathrm{CA.KLA} + \left(\frac{\mathrm{NREFA.KLA}}{N_A}\right)^2} \quad 3\text{-}225$$

where N_D and N_A are the donor and acceptor concentrations in cm^{-3} and CD.KLA, CA.KLA, NREFD.KLA, and NREFA.KLA are user-definable parameters as given in Table 3-45.

Table 3-45 User-Specifiable Parameters for Equations 3-224 and 3-225			
Statement	**Parameter**	**Default**	**Units**
MOBILITY	CD.KLA	0.21	
MOBILITY	CA.KLA	0.50	
MOBILITY	NREFD.KLA	4.0×10^{20}	cm^3
MOBILITY	NREFA.KLA	7.2×10^{20}	cm^3

Note: When the Klaassen low-field mobility is used, remember that it has been calibrated to work with Klaassen's models for bandgap narrowing, KLAAUG recombination, and KLASRH recombination. These models are described in the Section 3.6.3 "Carrier Generation-Recombination Models".

Uchida's Low-Field Model for Ultrathin SOI

The model by Uchida et.al. [272], provides a mobility limit in ultrathin-body MOSFET transistors with SOI thickness less than 4 nm. This mobility limit is due to thickness fluctuations in the nano scale SOI film. The model for electrons and holes is given by Equations 3-226 and 3-227.

$$\mu_{nu} = \mathrm{CN.UCHIDA} \cdot \mathrm{TN.UCHIDA}^{6} \quad \text{3-226}$$

$$\mu_{pu} = \mathrm{CP.UCHIDA} \cdot \mathrm{TP.UCHIDA}^{6} \quad \text{3-227}$$

The parameters CN.UCHIDA, CP.UCHIDA are calibrated from the reference to a default value of 0.78125 $cm^2/(V{\cdot}s{\cdot}nm^6)$. The parameters TN.UCHIDA and TP.UCHIDA represent the thickness of the SOI in µm. This value should as close as possible to match the physical thickness of the SOI layer in the simulated structure file. To enable this model for electrons and holes, specify values for TN.UCHIDA and TP.UCHIDA, and specify the logical parameters UCHIDA.N or UCHIDA.P or both on the MOBILITY statement. Table 3-46 lists the user specifiable parameters.

Table 3-46 User-Specifiable Parameters for Equations 3-187 and 3-188			
Statement	**Parameter**	**Default**	**Units**
MOBILITY	CN.UCHIDA	0.78125	$cm^2/(V{\cdot}s{\cdot}nm^6)$
MOBILITY	CP.UCHIDA	0.78125	$cm^2/(V{\cdot}s{\cdot}nm^6)$
MOBILITY	TN.UCHIDA	4.0	nm
MOBILITY	TP.UCHIDA	4.0	nm